

STUDY ON QUANTUM EFFICIENCY OF NEA-GaAs WITH VARIOUS THERMAL TREATMENTS; THE INCREASE IN QUANTUM EFFICIENCY BY THE LOW TEMPERATURE TREATMENT

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Abstract

Evolution of quantum efficiency (QE) is discussed in detail in relation to the history of conditions of negative electron affinity (NEA) activation and thermal pretreatment. An average QE of 0.10 was observed after multiple NEA activation with thermal pretreatment at 550 ° C, and a high QE of over 0.13 was observed with lower temperature activation (450 ° C). Our findings indicated that the increase in QE is caused by the number of electron emission sites due to the difference in the formation and desorption rates of Cs–Ga bonds.

INTRODUCTION

It is well known that vacuum-level lowering occurs at negative electron affinity (NEA) surfaces, which are formed by depositing alkali metal atoms on semiconductor or metal surfaces [1,2]. A GaAs surface covered by Cs is one of the basic structures of the NEA surface [3], and there have been similar reports for GaN and InGaAs [4,5]. NEA surfaces are expected to serve as novel nanoscale electron sources. The NEA photocathode has numerous advantages in electron sources with low emittance, high spin polarization, and high repetition rate [6,7]. Functional electron sources with high spin polarization, high repetition rate, or other unique features are attractive candidates for next generation electron microscopy. For future accelerator projects, e.g., ILC and ERL, the electron source is one of the most important components that determine the total performance of the accelerator.

NEA activation has to be carried out under ultra-high vacuum conditions because the NEA surface is seriously affected by the oxygen and CO₂ of residual gases [8], and the surface of NEA-GaAs photocathodes is damaged by back bombardment of ionized residual gas by photoelectrons [9]. We have observed in situ the NEA activation process by the surface photo-absorption method and have concluded that the two-step Cs adsorption process occurs on GaAs surfaces during NEA activation [10]. Various models of the NEA surface on semiconductors have been proposed for the NEA surface on semiconductors. Su et al. suggested the Cs⁺-O²⁻-Cs⁺ sandwich layer produces the NEA nature on the (110) GaAs surface [11], while Kim et al. reported that the Cs-adsorbed (100) GaAs surface is amorphous [12]; and, oxygen adsorption on the Cs-covered GaAs surface is

reportedly a dissociative process [13]. An NEA surface with a high quantum efficiency (QE) has been obtained by using the Yo-Yo method [14,15] upon an atomically clean surface after thermal treatment; however, the detailed structure of the NEA surface remains unknown.

In this study, we discuss the detailed relationship between the QE of NEA activation and the number and temperature of thermal treatments. We found that a lower temperature treatment provides higher QE under certain conditions.

EXPERIMENTAL PROCEDURE

The experimental setup used in this study has been reported previously [10] and is reviewed briefly here. A heater in a sample holder was used for elevating substrate temperature, and the temperature was measured by a thermocouple in contact with the backside of the holder. A vacuum chamber was evacuated to less than 3×10^{-8} Pa prior to the experiment by using an ion pump and Ti sublimation pump. Zn-doped p-type (100) GaAs substrates were used as samples.

Sample surfaces were thermally cleaned at 500 ° C for 1 h. Cs and O₂ were supplied alternately to the GaAs surface. Cs atoms were supplied by the sublimation of a Cs alloy, and O₂ pressure was controlled with a variable leak valve. A bias voltage of -40 V was applied to the sample for measuring the photoelectron emission induced by irradiation at 650 nm with a laser diode.

In the present experiment, the NEA activation procedures were repeated on the same GaAs specimen. The sample surface was thermally pretreated at 550 ° C or 450 ° C for 1 h. The sub-rate temperature was then gradually decreased to room temperature to lower the background pressure prior to the next NEA activation process. NEA activation was carried out at the same pretreatment temperature, and various NEA activation processes were performed as follows: First, NEA activation at 550 ° C was repeated multiple times (region [i] in Fig. 1); then the temperature was reduced to 450 ° C, and NEA activation was carried out three times (region [ii]). NEA activation at 450 ° C was again carried out after activation three times at 550 ° C (region [iii-a] and [iii-b]), and an additional two thermal pretreatments were done at 450 ° C under the conditions of regions (iii-a) and (iii-b) (region [iv]).

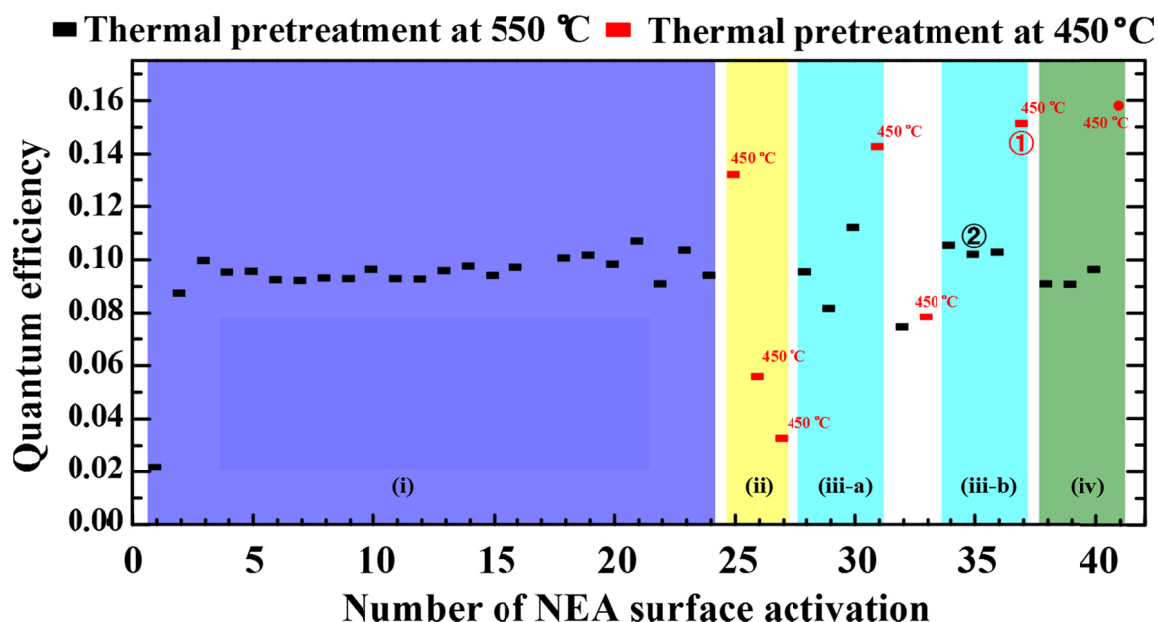


Figure 1: QE evolution after multiple NEA activation processes with various conditions. (i) NEA activation with thermal pretreatment at 550 °C. (ii) NEA activation with thermal pretreatment at 450 °C three times. (iii-a) and (iii-b) NEA activation with thermal pretreatment at 550 °C three times and NEA activation with thermal pretreatment at 450 °C. (iv) NEA activation with thermal pretreatment three times at 450 °C after NEA activation at 550 °C. The blue line indicates QE with activation at 550 °C; the red line shows QE at 450 °C. These QE were measured at points ① and ②.

RESULTS AND DISCUSSION

Figure 1 shows QE evolution after multiple NEA activation processes under various conditions. In region (i), the QE was 0.002 when the NEA surface was first activated at 550 °C. The QE increased to 0.085 following the second NEA activation and reached about 0.095 after repetitions of NEA activation. In region (ii) after experiments in region (i), we observed a higher QE (0.13) than that observed in region (i). After repeating the same process at 450 °C, the QE notably decreased to 0.06 and 0.03. In region (iii-a), we confirmed the QE evolution observed in regions (i) and (ii). When NEA surface activation was again carried out at 550 °C, the QE recovered to 0.10. After repeating NEA activation at 550 °C two more times, a higher QE of 0.14 was again obtained by NEA activation at 450 °C (as well as in region [ii]). In region (iii-b), experimental conditions were the same as in region (iii-a), and the QE showed the same tendency with a high QE obtained at 450 °C immediately after 550 °C NEA activation. The observed QE was about 0.10 by NEA activation at 550 °C and 0.15 after successive 450 °C NEA activation. In region (iv), additional thermal pretreatment was performed, but the QE obtained after 450 °C NEA activation immediately after 550 °C activation most the same in all region.

Figure 2 shows the time course of QE during NEA activation. The first QE peak with NEA activation at 450 °C and 550 °C was 0.003 at 10.1 min and 0.005 at 10.9 min, respectively. After the second QE peak, the peaks depended on the amount of Cs and O₂; however,

eventually QE at 450 °C NEA activation increased beyond that of 550 °C NEA activation.

It is interesting that the higher QE was realized by NEA activation at a lower temperature. QE was constant during repetition of NEA activation at 550 °C, and QE abruptly decreased with repeated activation at 450 °C; however, the low QE increased to its previous value by 550 °C NEA activation. The results seen in region (iv) show that additional thermal pretreatment does not influence the level of QE. We conclude that the surface differs during the NEA activation process with thermal pretreatment at 550 °C versus 450 °C.

The difference in surfaces during NEA activation at 450 °C and 550 °C is considered to be caused by the number of electron emission sites. In region (i), formation and desorption rates of the emission sites are balanced, and therefore a constant QE was observed. On the other hand, desorption of emission sites was suppressed at 450 °C and so a higher QE was realized. However, thermal pretreatment at 450 °C was insufficient for completely cleaning the surface so that the QE abruptly decreased with repetition of NEA activation.

We confirmed by scanning tunneling microscopy measurements that the Cs atoms do not bond with surface As atoms [16]. It has also been reported that Cs adsorption on the As-rich GaAs surface induces conversion to a Ga-rich reconstruction by annealing at 450–470 °C [17]. It is considered that Cs-Ga bonding to be the main electron emission site, and the number of Cs-Ga bonds is related to the QE. Present results suggest that the Ga-terminated surface is obtained after higher temperature conditions, and a lower temperature is

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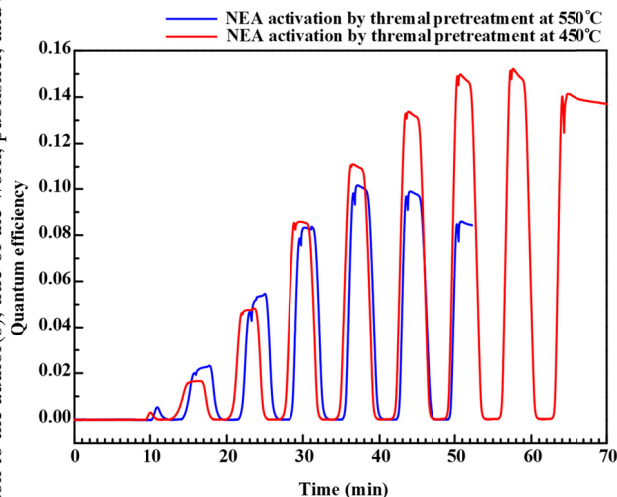


Figure 2: The blue line indicates the time course of QE during NEA activation with thermal pretreatment at 550 °C; the red line shows the QE in NEA activation with thermal pretreatment at 450 °C.

preferable for the suppression of desorption of the formed electron emission site.

SUMMARY

We investigated NEA activation of a p-type GaAs surface by thermal pretreatment at 550 °C or 450 °C. A QE of 0.10 on average (standard deviation of 0.07) was observed in NEA activation at 550 °C. A high QE of over 0.13 was observed with NEA activation at 450 °C. In order to obtain a high QE, NEA activation must first take place at a higher temperature (550 °C) followed by NEA activation at a lower temperature (450 °C), and the repetition of NEA activation at 450 °C caused the QE to degrade. We consider that the difference in QE derives from the number of electron emission sites due to the difference in the formation and desorption rates of the Cs-Ga bonds.